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# CDF Silicon Tracking Detectors, 1988–2011

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**Abstract**

On September 30, 2011, the Collider Detector at Fermilab (CDF) finished physics data-taking at the Tevatron proton-antiproton collider. The original CDF silicon tracking detector, proposed in 1981 (SVX) and later replaced and updated (SVX′), was again replaced for Run-2 in 2002–2011 (SVX-II, ISL, L00). These systems operated successfully for many years, performing essential roles in exploring physics at the energy frontier, most notably the discovery of the top quark.

*Keywords:* CDF, SVX, SVX', SVXII, ISL, L00, microstrip sensor

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## 1. Run-1 silicon

The application of silicon detectors for high-energy physics began to be explored in the beginning of the 1980s for detecting short lived particles [1]. An important breakthrough in 1980 was the demonstration of the production of silicon detectors using the standard planar process [2], which led to the industrialization of sensor production.

The addition of silicon tracking to the CDF vertex region was originally presented in 1981 in its technical proposal [3]. The application of VLSI readout [4], [5] presented in 1984 was a key step towards realizing the high density silicon trackers at colliders. In spring 1985 a workshop was held to discuss the SVX. Although most of the LEP detectors were installing silicon tracking, application to CDF was considered very challenging due to technical issues such as long SVX strips and 50k signals to readout. The project was pushed forward by development of a new CMOS ASIC, the SVX chip [6], with sophisticated logic added to improve S/N and to allow sparse readout and double-correlated sampling. The SVX proposal was approved in 1988.

The SVX [7], [8] employed 8.5 cm long Micron sensors having a 55-60 $\mu$m pitch. The sensors were DC-coupled since AC-coupling was considered not a sufficiently mature technology at that time. Three sensors were glued to a Rohacell support to form a light-weight ladder structure, and wire-bonded to read out with SVX ASICs (revision D) from one end. Fig. 1 shows an SVX barrel consisting of four ladder layers, each ladder covering a 30° section. Two barrels were installed end-to-end, and operated in the experiment (1992–93) for an integrated luminosity of 30 pb$^{-1}$. Because of the radiation-soft design of the readout chip, the S/N degraded from 9 to 6 for the innermost layer.

Figure 1: One of the two completed SVX barrels.

The sensors for the second system SVX′[9] were AC-coupled with FOXFET biasing [10]. The use of poly-silicon resistors as a biasing method was not pursued since the technology was not considered sufficiently mature at that time. The fabrication technology for the new readout ASIC SVX(rev.H) was UTMC 1.2 $\mu$m rad-hard CMOS technology (HP 3.5 $\mu$m for SVX(rev.D)), enhancing the radiation tolerance. The SVX′ was installed in 1993 and operated till the end of Tevatron Run-1, 1996.

## 2. Run-2 silicon

Experience with SVX′ demonstrated the importance of good vertex resolution to maximize the broad physics program at the Tevatron. To cope with the higher luminosity ($10^{32}$ cm$^{-2}$s$^{-1}$) and shorter bunch spacing (132 ns in design - 395 ns actual),

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the inner tracking was re-designed.

Fig. 2 illustrates the Run-2 silicon tracking, which covered the radial region from the beampipe to a radius of 32 cm. The SVX′ region was replaced with SVX-II, which served as the main silicon tracker. The Intermediate Silicon Layers (ISL) are located outside this, and Layer 00 (L00) was attached on the beampipe. Main sensor parameters and manufacturers are listed in Table 1.

The readout was made with the Honeywell 0.8 $\mu$m SVX3 chip[11] where a 46 deep analog pipeline enabled deadtimeless operation.

Table 1: Main sensor parameters of Run-2 silicon detectors.

| Layer (radius[cm]) | Axial/stereo pitch[$\mu$m] | Stereo angle | Manuf. |
|---|---|---|---|
| L00 (1.35) | 25/– | – | Thompson, Micron |
| L00 (1.62) | 25/– | – | HPK |
| L0 (2.7) | 60/141 | 90 | HPK |
| L1 (4.3) | 62/125.5 | 90 | HPK |
| L2 (6.7) | 60/60 | 1.2 | Micron |
| L3 (8.4) | 60/141 | 90 | HPK |
| L4 (10.3) | 65/65 | 1.2 | Micron |
| ISL (20, fw) | 112/112 | 1.2 | HPK |
| ISL (23, cnt) | 112/112 | 1.2 | HPK |
| ISL (29, fw) | 112/112 | 1.2 | Micron |

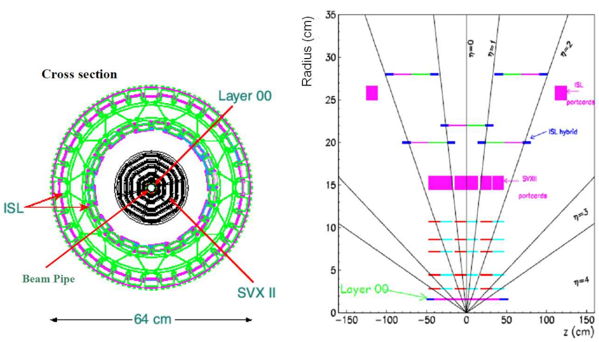


Figure 2: Run-2 silicon tracking system, consisting of SVX-II (five double-sided), ISL (one in the central and two double sided in the forward), and L00 (one single sided) detectors.

### 2.1. SVX-II

The design and performance of the SVX-II detector are described in detail in Ref. [12]. The goal for SVX-II was to maximize the precision tracking capability by extended $\eta$ coverage and "3D-vertexing", with precision track information in both $r$-$\phi$ and $Z$. Following the success of SVX′, it was important for SVX-II to be aggressive in design.

Fig. 3 shows the photograph of one of the ladders. The ladder was constructed on a structure formed out of boron-carbon fiber and Rohacell foam, to which four silicon sensors were glued. Two BeO ceramic boards were glued on the surface of the sensors at the both ends. The ladders, 5 layers times 12 sections in $\phi$, were attached to beryllium end plates with integrated cooling. The SVX-II was composed of three identical barrels, each being 32 cm long. The total SVX-II length of 96 cm was necessary to cover the long interaction region of the Tevatron (30 cm $\sigma$), which improved the event acceptance for top and bottom decays by typically 50% over the 51 cm long SVX′.

An innovative track-based trigger was implemented in a dedicated online processor, the Silicon Vertex Tracking, SVT [13], [14]. SVT imposed stringent requirements on the detector design and construction to achieve alignment of the strips parallel to the beam direction to within 100 $\mu$rad. Each ladder was constructed to an alignment tolerance of 5 $\mu$m, and the three barrels were aligned to well within 30 $\mu$m by using a common carbon fiber spaceframe. With the success of this new trigger, CDF became competitive with the B factories, opening the sector of heavy hadrons that were not accessible to the B factories.

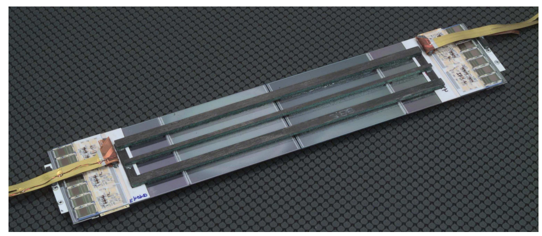

Figure 3: One of the SVX-II ladders. The length is 32 cm.

In order to reduce multiple-scattering of low momentum tracks, the material thickness was minimized by using double sided sensors. In order to provide both optimal three dimensional vertex resolution and good track reconstruction efficiency, three of the five layers (L0, L1 and L3) employed strips at 90° and the other two layers (L2 and L4) used 1.2° small angle stereo strips. Track reconstruction in the $r$-$\phi$ plane was given the highest priority, and this was chosen as the $p$-side of the sensor (as for SVX′) which was the more standard choice at that time. The 90° readout was realized by adopting a double metal structure, applied to the ohmic side of the sensors since this was consider to incur additional risk.

The concept of double-metal readout is illustrated in Fig. 4. The readout metal and silicon electrodes are connected by vias through a 5 $\mu$m thick $SiO_2$ insulator. Since the electronics is at the ends of the ladders, the number of channels in the 90° readout is limited by the number of readout chips that can fit within the width of the ladder. To allow acceptable strip pitches (and therefore good resolution), several strips were multiplexed onto the same readout channel in the double-metal layout. These strip pitches (125 $\mu$m for L0 and L3, and 141 $\mu$m for L1) required extensive $p$-stop development and careful checks of capacitance to ensure good charge collection.

The adopted design was a "combined" p-stop structure, which gave a minimum capacitance among several designs, as shown in Fig. 5 [15]. The overall readout capacitance was 24, 36 and 28 pF for L0, L1 and L2, respectively. The degradation of signal collection between the strips was also minimal with the combined structure [15]. Intensive studies carried out on test structures of different pitches and other parameters, and

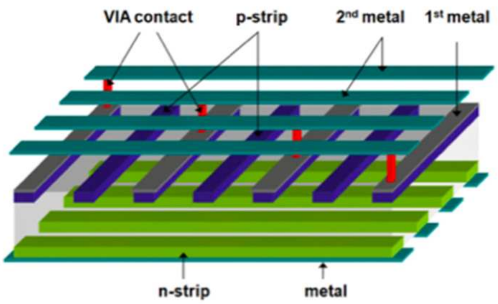


Figure 4: The concept of the double metal readout employed for SVX-II 90° sensors.

the use of high-precision laser scans, were innovations at the time. Also, radiation damage, type inversion, and the biasing scheme adopted in this double-sided detector significantly complicated the design [16]. The production of prototype, "pilot" and production sensors was a necessity, and had to be carefully managed. A liaison with close ties to the manufacturer proved critical to the successful realization of this state-of-the-art microstrip detector.

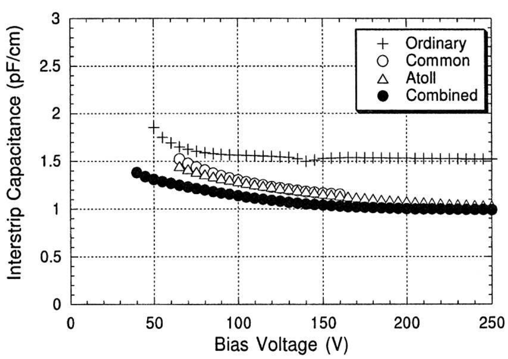


Figure 5: Interstrip capacitance compared among different p-stop structures [15]. "ordinary" is *p*-spray.

### 2.2. Intermediate Silicon Layers, ISL

Located between the SVX-II and the Central Outer Tracker (COT) wire drift chamber, the ISL [17] was designed to provide the anchor hit points in connecting the two track segments in these detectors, and also to perform standalone tacking in the forward regions ($0.5 < \eta < 1.0$) where the COT coverage was limited. The sensors were double-sided with 1.2° stereo-angle, and were fabricated on 6-inch wafers. One "ladder" contains four 9.6 cm long sensors, where the readout ceramic boards were glued on the sensors at both ends. Such ladders were arranged in one barrel layer, and two layers in each of the forward regions.

### 2.3. L00

The L00 detector [18] was proposed to improve the secondary vertex resolution. The sensors were LHC-style single-sided. The sensors were designed for operation at high bias voltages, allowing the detector to operate well for the full 12 fb$^{-1}$ integrated luminosity of Run 2, well beyond the 3 fb$^{-1}$ originally specified.

Six inner (128 strips) and six outer (256 strips) sensor groups covered the beampipe at $r$=1.35 cm and 1.62 cm, respectively. Each group consisted of six readout modules along the beam with two sensors from 6" wafer bonded together in each module. The total detector length was 94 cm. The sensors were mounted on the cooling system integrated carbon-fiber structure which was glued directly to the beampipe. The readout hybrid boards were placed away from the beam via 50 $\mu$m thick polyimide film. The longest film cable was 47 cm, having a capacitance of 17 pF.

The implant pitch of the sensor was 25 $\mu$m while the readout was at 50 $\mu$m pitch. One group of the inner sensors was oxygenated silicon from Micron.

## 3. Detector Operation

### 3.1. Commissioning and operation

In the commissioning phase, several problems were encountered. We summarize some of these experiences here.

A substantial part (1/3) of the ISL cooling lines were blocked at the innermost joints by epoxy. This was not found from flow and leakage tests performed during construction, but found using custom borescopes after the detector installation. The problem was fixed by burning holes into the blockages using medical laser without damaging the Al cooling pipes.

Another well known experience, this time for the SVX-II detector, was the occurrence of resonant vibrations of wirebonds in the magnetic field [19]. Due to the tight space constraints for SVX-II, small ceramic circuits with via connections were used to transfer the data and control signals between the hybrid circuits on the two sides of the ladder, and these were connected electrically using wirebonds. When operating in the CDF solenoid field at a high trigger rate (~10 kHz), the Lorentz forces caused by bursts of data across these bonds produced resonant variations that occasionally resulted in bonds breaking, and the loss of data from the $Z$ sided of the ladder. After detailed investigations, the problem was solved with development of a protection circuit in the trigger logic that prevented repeat triggers with a frequency near a wirebond resonant frequency. This introduced negligible dead time for the experiment.

The pedestals from L00 showed patterned distributions across the sensors, which was caused by long polyimide readout lines acting as antenna. Improvement on shielding was tried but not successful enough. Since the SVX3 was not implemented with the individual pedestal tuning, we decided to take all the data and subtract the pedestals in offline, which was possible given the small number of L00 channels, 14k in total.

The ISL coolant was changed from 100% water to 90/10 water/ethylene glycol from April 2005 for lower freezing point, but switched back to pure water from April 2007. The coolant was set back because the ISL cooling lines showed degraded vacuum due to leaks. Investigation with borescopes revealed the existence of holes near the manifold joints, and chemical analysis measured the coolant too high in conductivity and too low in PH (~2), suggesting that the holes were caused by corrosion. The problem was fixed during a shutdown by adding epoxy around the manifold joints. The SVX-II system also used 70/30 water/ethylene glycol with beryllium instead of aluminum tubing used for ISL. Glycol degradation into organic acids could be the reason for aluminum corrosion.

The evolution of the fraction of the working ladders is shown in Fig. 6 [20],[21] for the whole Run-2 period starting from 2002 to the end. After a significant ramp-up time in 2002, the detector became fully operational, with 93% of the ladders powered and 85% giving data with an error rate of less than 1%. These numbers were maintained at a high level, dropping only a few %, over the whole period of nine years.

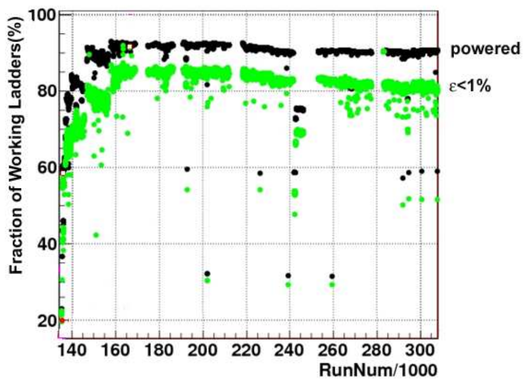


Figure 6: Fraction of working ladders from 2002 to 2011, (black) powered ladders and (dark) ladders with error rate less than 1%.

### 3.2. Silicon longevity

The silicon system had been designed for an operational lifetime to beyond 2 fb$^{-1}$, but continued working as shown in Fig. 6. The lifetime of the detector is limited by increases of the full depletion voltage and noise due to radiation.

The depletion voltage was extracted from dedicated collider runs where the collected charge distributions were obtained with various biases. The full depletion was defined at the bias the charge collection is 95% of the plateau.

Fig. 7 shows the evolution of L00 sensor depletion voltage. The full depletion voltage is plotted as a function of irradiation dose for sensors fabricated by each of the three vendors: Hamamatsu Photonics, SGS-Thompson, and Micron Semiconductor. All sensors have progressed through inversion, exhibiting consistent post-inversion development. Among these, oxygenated Micron sensors show the smallest change with radiation. The inner layers of SVX-II also showed similar dependence, as shown in Fig. 8.

The evolution of signal-to-noise ratio is plotted in Fig. 9 for the $Z$ side. The signal charge was calculated using $J/\psi \to \mu^+\mu^-$ tracks, while the noise was estimated from regular calibrations performed in no beam conditions.

Tevatron Run-2 was expected to provide a total integrated luminosity of 15 fb$^{-1}$, and it was expected that this would require replacement of the inner silicon layers in a Run-2b silicon upgrade project initiated in 2003 [22]. Subsequently, detailed

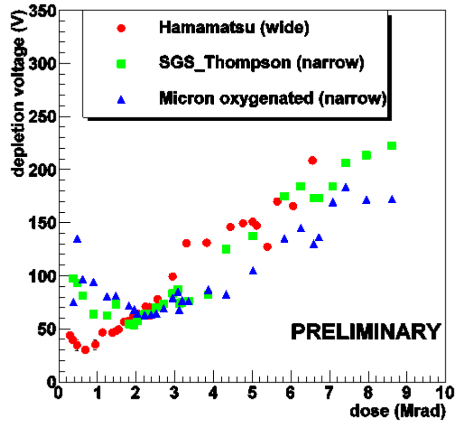


Figure 7: Evolution of the full depletion voltage for L00 sensors. 0.72-0.95 Mrad/fb$^{-1}$ for outer-inner sensors.

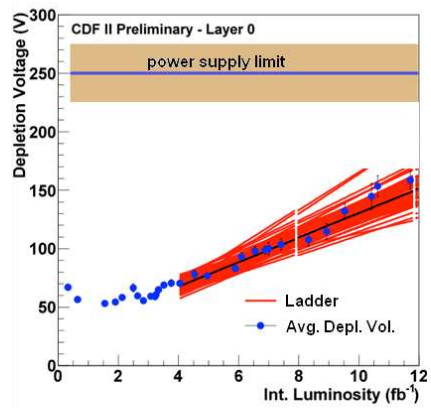


Figure 8: Evolution of the full depletion voltage of SVX-II Layer-0.

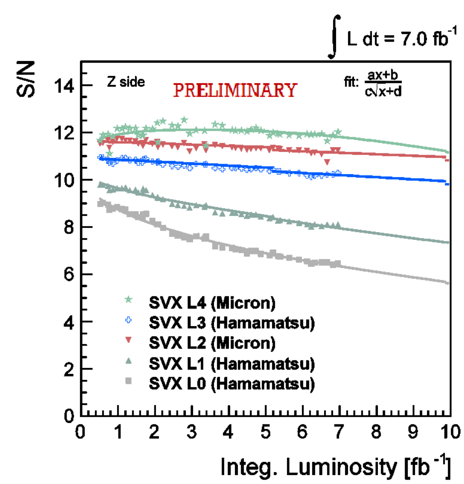


Figure 9: Evolution of the signal-to-noise ratio for $Z$ side sensors.

lifetime studies for the operating detector indicated that it would survive to an integrated luminosity approaching the maximum expected [23], and so the Run-2b project was canceled. Indeed, with careful operation over many years, the detector performed very well for the full 12 fb$^{-1}$ accumulated to the end of operation of the Tevatron accelerator.

## 4. Conclusions

The CDF silicon tracking detectors have been operated successfully to the end of the Tevatron 1.96-TeV $\bar{p}p$ collider program, having played an essential role in achievements in the physics program. In addition they have significantly progressed silicon microstrip technology, by realizing state-of-the-art sensors such as the double-sided double-metal devices employed in the SVX-II detector, and also simple single-sided radiation-hard sensors employed in L00. The technology of the latter transferred directly to the LHC experiments. The CDF silicon detectors are at present being investigated for their annealing characteristics. Since the detectors experienced intensive irradiation in long periods, these data should provide unique insight on the annealing.


## Acknowledgements

Professor Takashi Ohsugi led the sensor design for the SVX-II silicon detector, where L0, L1, and L3 provided 3-dimensional 90° readout in a ladder geometry using an innovative double-metal technique. These sensors were designed by Takashi, and fabricated by Hamamatsu Photonics. Takashi is not only a technical leader, but an esteemed colleague and friend. On behalf of CDF we would like to congratulate Takashi on such an influential career and wish him a wonderful and very well-earned retirement.

This manuscript is prepared based on the quoted many documents as well as intensive works prepared for recent conferences. We would like to acknowledge those people who have conducted the study, and also many people who contributed to the detector construction and operation.


## References


[1] M. Turala, Nuclear Instruments and Methods A541 (2005) 1.
[2] J. Kemmer, Nuclear Instruments and Methods 169 (1980) 499.
[3] D. Ayres, et al., Fermilab, Tech. Rep. (1981).
[4] R. Hofmann, et al., Nuclear Instruments and Methods 226 (1984) 196.
[5] J. Walker, et al., Nuclear Instruments and Methods 226 (1984) 200.
[6] S. Kleinfelder, et al., IEEE Trans. Nucl. Sci. 35 (1988) 151.
[7] W. Carithers, et al., Nuclear Instruments and Methods 289 (1990) 388.
[8] S. Tkaczyk, et al., Nuclear Instruments and Methods A342 (1994) 240.
[9] P. Azzi, et al., Nuclear Instruments and Methods 360 (1995) 137.
[10] P. Allport, et al., Nuclear Instruments and Methods 310 (1995) 155.
[11] T. Zimmerman, et al., Nuclear Instruments and Methods 409 (1998) 369.
[12] D. Amidei, et al., Nuclear Instruments and Methods A350 (1994) 73.
[13] W. Ashmanskas, et al., Nuclear Instruments and Methods A447 (2000).
[14] L. Ristori, The history of the cdf silicon vertex trigger, 2011. Talk presented at TIPP2011, Chicago, USA.
[15] Y. Iwata, et al., IEEE Trans. Nucl. Sci. 45-3 (1990).
[16] T. Ohsugi, et al., Nuclear Instruments and Methods A436 (1999).
[17] A. Affolder, et al., Nuclear Instruments and Methods A453 (2000) 84.
[18] C. Hill, et al., Nuclear Instruments and Methods A530 (2004) 1.
[19] G. Bolla, et al., Nuclear Instruments and Methods A518 (2004).
[20] M. Stancari, Cdf tun-ii silicon detector: Operation and aging, 2011. Talk presented at Vertex2011, Rust, Austria.
[21] B. Di Ruzza, Operation experience and aging studies of the cdf run ii silicon vertex detector, 2011. Talk presented at TIPP2011, Chicago, USA.
[22] T. Akimoto, et al., Nuclear Instruments and Methods A556 (2006) 459.
[23] S. Worm, Nuclear Instruments and Methods 549 (2005) 126.